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Recent advances in automatic alignment system for the National Ignition Facility

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ABSTRACT

The automatic alignment system for the National Ignition Facility (NIF) is a large-scale parallel system that directs all 192 laser beams along the 300-m optical path to a 50-micron focus at target chamber in less than 50 minutes. The system automatically commands 9,000 stepping motors to adjust mirrors and other optics based upon images acquired from high-resolution digital cameras viewing beams at various locations. Forty-five control loops per beamline request image processing services running on a LINUX cluster to analyze these images of the beams and references, and automatically steer the beams toward the target. This paper discusses the upgrades to the NIF automatic alignment system to handle new alignment needs and evolving requirements as related to various types of experiments performed. As NIF becomes a continuously-operated system and more experiments are performed, performance monitoring is increasingly important for maintenance and commissioning work. Data, collected during operations, is analyzed for tuning of the laser and targeting maintenance work. Handling evolving alignment and maintenance needs is expected for the planned 30-year operational life of NIF.

Keywords: control systems, laser alignment, National Ignition Facility, automatic alignment

1. INTRODUCTION

The National Ignition Facility (NIF) is a 192-beam pulsed laser system constructed and tested at the Lawrence Livermore National Laboratory (LLNL). NIF has become an international center for the study of inertial confinement fusion and the physics of extreme energy densities and pressures. NIF experiments allow the study of physical processes at temperatures approaching 100 million K and pressures 100 billion times atmospheric. These conditions exist naturally in the interior of stars and in nuclear weapons explosions [1]. In September 2004, the first four NIF beams (a “quad”) were commissioned to the center of the target chamber, which demonstrated end-to-end functionality for all major subsystems. In September 2008, all 192 beams were commissioned, making NIF the most energetic laser in the world. In 2009, NIF began experiments providing energetic laser beams to, among other goals, compress deuterium-tritium fusion targets to conditions where they will ignite and burn. Ignition experiments are in progress with the plan to liberate more energy than is required to initiate the fusion reactions. The NIF building consists of two laser bays, four capacitor areas, two laser switchyards, the target area, and a core area that contains the control room and master laser oscillator. The laser is configured in four clusters of 48 beams per cluster. Each laser bay contains two clusters (Fig. 1). Each cluster has six sets of eight beams called bundles (NIF has 24 bundles), which is the fundamental beam grouping in the laser bay. At the switchyard, each bundle is split into two quads, with one quad from each bundle directed toward the top of the chamber and the other directed toward the bottom.

NIF is controlled by a large-scale integrated computer control system (ICCS) [2]. ICCS is a layered architecture with the lowest layer comprised of 750 front-end processors. At the upper layer, ICCS is coordinated by supervisory subsystems including automatic beam control, laser and target diagnostics, pulse power, and shot control. ICCS software is based on an object-oriented framework using CORBA that incorporates services for archiving, machine configuration, graphical user interfaces, monitoring, event logging, scripting, alert management, and access control [3]. Coding in a mixed-language environment of Java and Ada is mostly complete with over 1.5 million source lines deployed. Given the long term challenges of Ada, the ICCS code base is migrating to Java. Most of the new code is devoted to changing requirements, or coding language translation. ICCS operates the laser and target area equipment to automatically setup and fire shots [4]. The process which coordinates the setup, adjustment, and verification for all devices in NIF for a laser pulse experiment is called a "Shot Cycle". A major goal of NIF is to complete a shot cycle routinely every four-hours.

The automatic alignment system is responsible for aligning all 192 beamlines along the 300-meter optical path to focus precisely at spots on the 10-mm-sized target with a tolerance of 10 microns. In an analogy to baseball, this is like hitting the strike zone with pitch thrown from 350 miles away. Automatic alignment runs within the apportioned 60 minutes of the four-hour shot cycle, which requires the system to function reliably and quickly without operator intervention. As of Nov 19, 2009, automatic alignment has successfully participated in 427 shots to the target chamber. In this paper, we will focus on improvement to the system since our last report [5].

2. ALIGNMENT REQUIREMENTS

Forty-five separate optical adjustments are required on each of the 192 beams prior to the shot (Fig. 1). Each optical adjustment is managed by a control loop. A control loop coordinates device movements and image processing tasks while mediating resources shared between loops. The automatic alignment system is comprised of 25 separate control systems for the 24 independent bundles and the target area. Each beam is further organized into four parallel segments that can be independently aligned. In total, there are 4,336 closed loop adjustments using 12,000 devices. The number of closed-loop adjustments required for NIF shot operations has grown from 3,800 to 4,336 since 2007. This increase in control loops is due to the addition of hardware needing alignment and the refinement of the alignment process to achieve more accuracy and operational robustness.

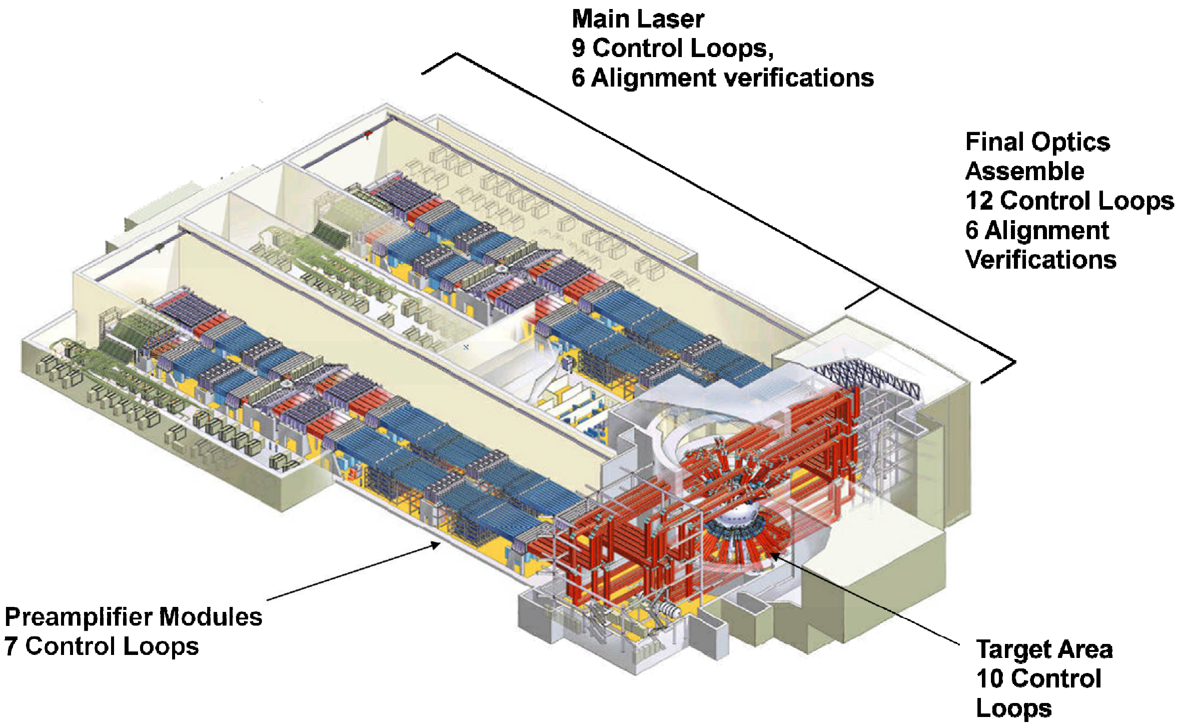

Figure 1: The National Ignition Facility incorporates 3,680 closed-loop alignment operations.

During routine shot operations, two operators on two control room consoles manage the NIF alignment using the automatic system (Fig. 2). Operators are able to manage the large number of adjustments due to extensive automation. The majority of operator work is to monitor automated operation and correct off-normal conditions. Off-normal image detection is required to qualify images before feature location is attempted [6]. In off-normal situations, the operator is alerted to bring manual controls online for the affected beam to correct the problem. The operators then resume the automatic process.

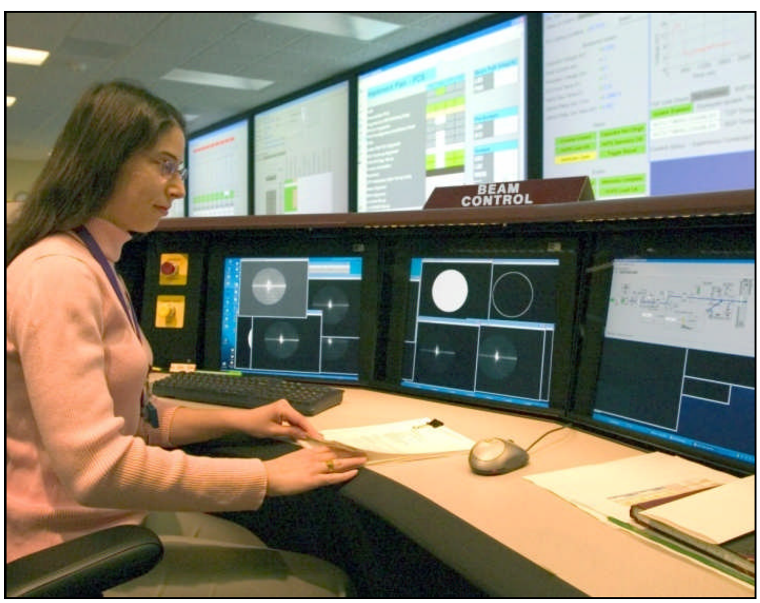

Figure 2: Beam control operator in the NIF control room.

Control loop operations can be generalized into two types: centering and pointing (Fig. 3). Centering operations are required to position the beam on the optical clear aperture of mirrors and lenses, so it stays constrained within the beam tube. Centering tolerances range from 0.01 to 3.0 mm. Pointing operations correct the angle of the beam traveling down the beam tube. Pointing tolerances range from 0.135 to 10 micro radians.

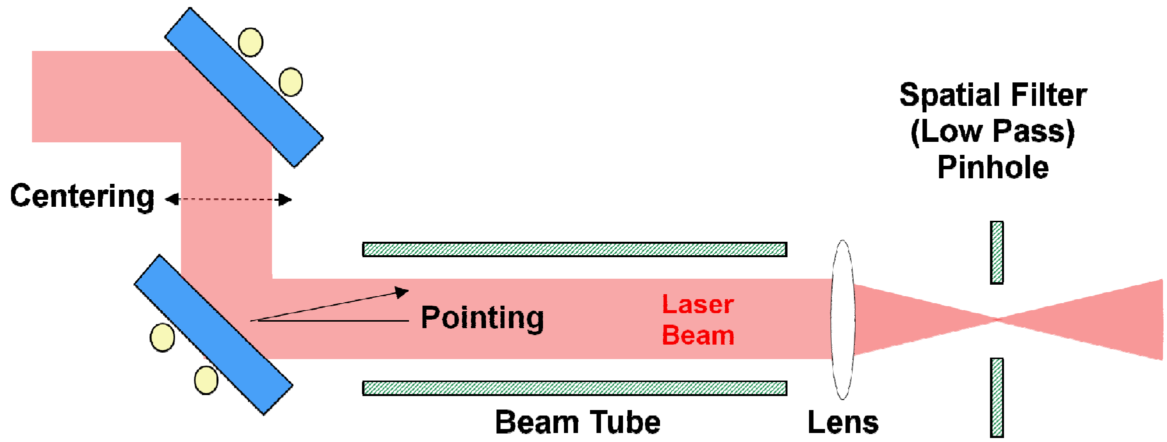

Figure 3: General definition of pointing and centering.

2.1 Changing requirements

NIF is planned to be an operational facility for 30 years. As noted earlier, the number of adjustments required for each shot has grown from 3,800 to 4,336. As the NIF laser operations evolve, refinement of laser alignment operations will continue. The growth in number of control loops has progressed from the addition of new devices requiring alignment as well as the refinement of existing alignment techniques to improve alignment accuracy and robustness. In addition to the shot alignment control loops, there is a growing number of maintenance and commissioning operations utilizing new control loops. The maintenance and commissioning control loops are tools to deal with the installation of new hardware and the calibration of systems. These maintenance and commissioning operations are done outside of a shot cycle.

This paper will not attempt to describe all the changes in alignment or maintenance and commissioning upgrades, but will focus on two illustrative updates:

- The Target Alignment Sensor

- The addition of the Ice Layer Characterization Alignment system.

2.2 Third-Generation Target Alignment Sensor Installed on NIF

Installation and commissioning of NIF's ignition target alignment sensor (ITAS) began in late April 2010. The ITAS is a sophisticated precision optical system to align the NIF beams and the target (Fig. 4). Mounted on the massive ITAS positioner and inserted into target chamber center, the ITAS allows NIF's operators to see how the beams will fall onto the target without any beams actually hitting the target. Horizontal mirrors of the ITAS intercept alignment laser beams coming from the top and bottom of the target chamber, and redirect the light to the upper and lower ITAS cameras. The ITAS cameras also image the target and provide precision alignment of both alignment of the target and the aiming of beams onto the target. Before an ignition shot, the ITAS is removed allowing the high powered laser pulse to reach the target.

The ITAS is the third-generation alignment sensor designed to align the laser beams with ignition hohlraums. It also includes improved cameras and a new thermal management design to meet the stringent stability requirements. The ITAS is critical to meeting the precise pointing requirements which ensure uniform irradiation of the NIF target capsule.

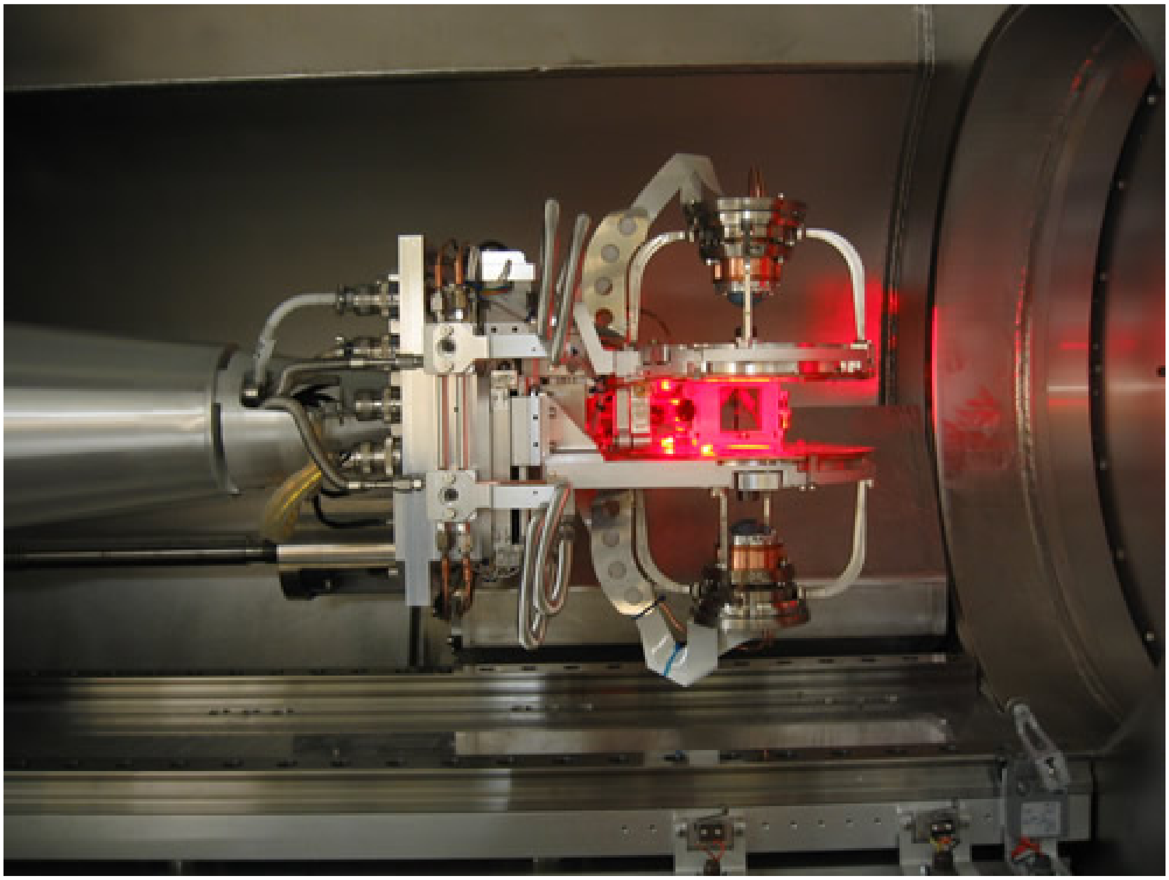

Figure 4: NIF's third-generation ignition target alignment sensor in action.

The ITAS is aligned to the center of the target chamber with feedback from four cameras. These four cameras are mounted on the target chamber equator at two orthogonal locations. These cameras measure the position in three dimensions, and the roll and pitch of the ITAS. The cameras are movable and allow imaging of the ITAS at any position within a 10 cm cube at the center of the target chamber. With this feedback, in 2009, the ITAS was routinely positioned to an accuracy of 20 microns for any specified position within the 10 cm cube at the target chamber center.

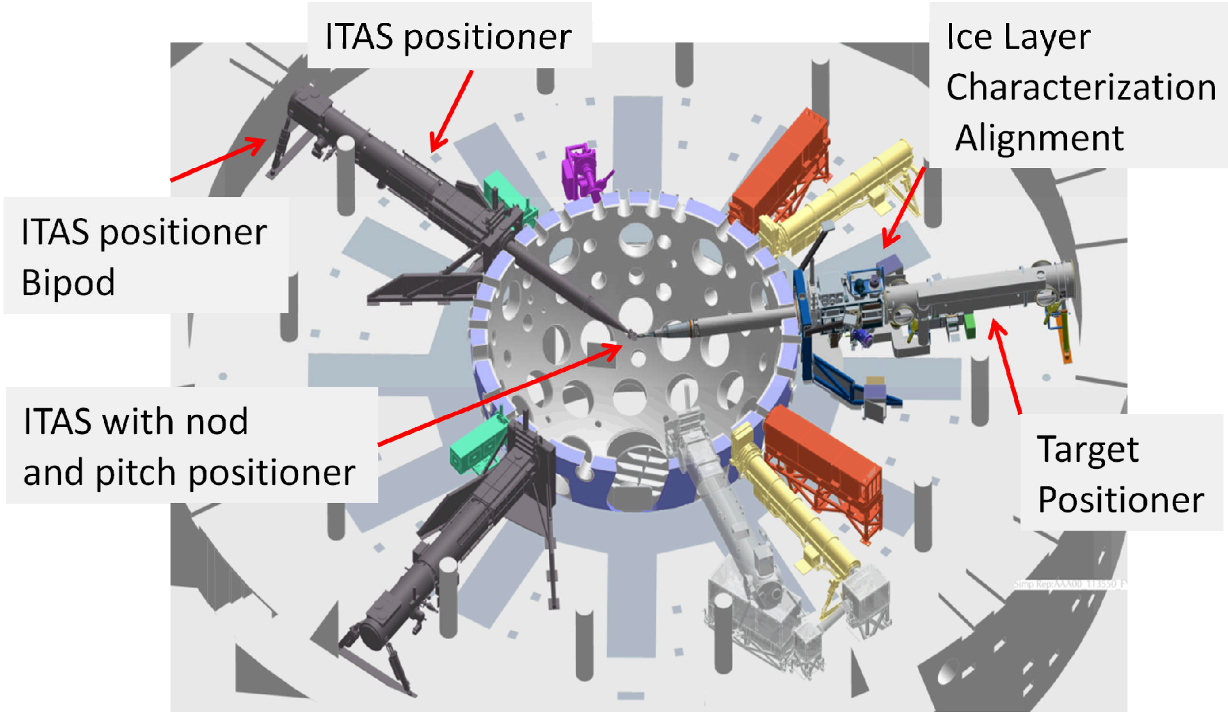

Figure 5: The ITAS positioner bipod (at left) and the nod and pitch positioners (at center) are parts of the ITAS positioner. The ITAS positioner and cryogenic target area positioner are inserted at target chamber center.

The main positioning of ITAS is controlled by the ITAS positioner in figure 5. The ITAS positioner contains a 15-foot telescoping pole with a nod and pitch positioner holding the ITAS and centered in the target chamber. At the base of the ITAS positioner is the bipod positioner. The bipod positioner is shown in lower right of Figure 6. The bipod positioner controls the tail end of the telescope pole holder. Using the side of the target chamber as a fulcrum, the bipod positioners can move the end of the ITAS positioner near the target chamber center, thereby adjusting the position of the ITAS.

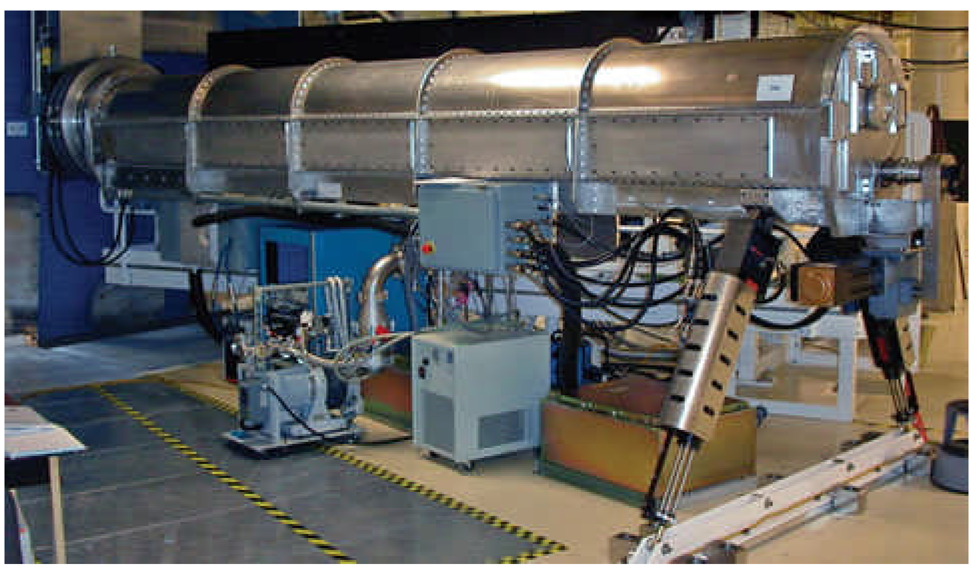

Figure 6: ITAS positioner connected to equator of the NIF target chamber

In 2010, through monitoring of the stored operational data and ITAS testing, alignment uncertainty of the ITAS position was identified as caused by the mechanical backlash of the ITAS nod motor positioner. With the knowledge of the error source, the alignment process was modified. The first step of ITAS alignment still uses the full complement of ITAS positioner motors to align to an accuracy of 20 microns. Then, an additional control loop was added. This new loop skips using the ITAS nod positioner and thereby avoids the backlash error. With the addition of this control loop, the alignment accuracy of the ITAS was improved to 10 microns. This is one example of the many updates for the automatic alignment system due to the refinement of the alignment process.

2.3 Ice Layer Characterization Alignment system

In addition to the evolutionary changes of the existing automatic alignment system, we continue to add new systems requiring alignment. An example of a new system requiring alignment is the ice-layer characterization system. The ice-layer characterization system is used as part of the hohlraum manufacturing process. The hohlraum is a cylinder that measures just nine millimeters high by five millimeters in diameter and is made of high density metal such as gold and uranium (Fig. 7). Centered in the hohlraum is a 1-mm diameter sphere, or capsule, containing hydrogen fuel that is cryogenically cooled to form a frozen layer inside the sphere. After the completion of the ice layer fabrication, the hohlraum is inserted into the NIF target chamber and setup for an ignition shot experiment.

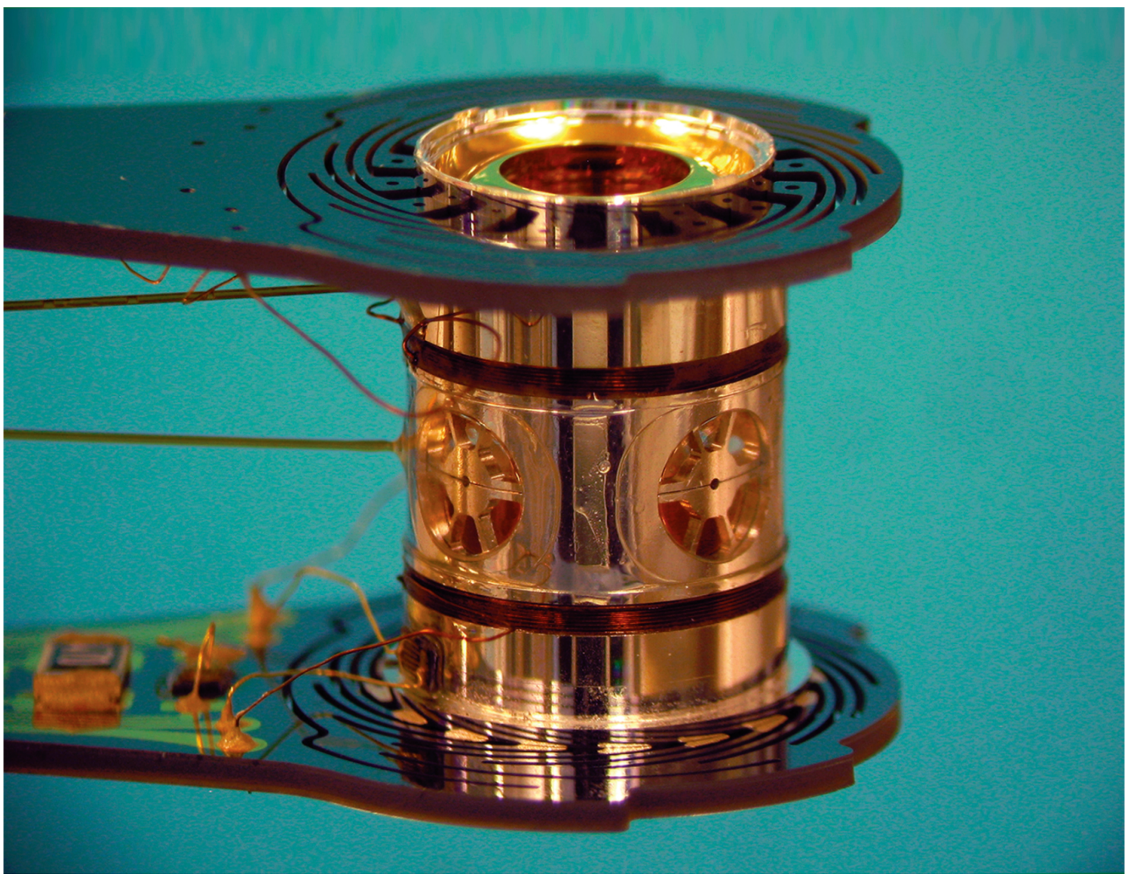

Figure 7: Hohlraum mounted on two horizontal thermo isolation rods

The uniformity of the ice-layer is critical to the efficiency of the implosion of the hydrogen during a shot. The manufacturing requirements for the ice-layer are a thickness 70 microns with a tolerance +/- one micron over the entire sphere. If cracks or non-uniformities occur, the ice-layer needs to be melted and reformed. To confirm the ice-layer tolerances, the capsule is imaged with x-rays from three directions.

The measurement of the ice layer is complicated by the fact that the high density metal of the hohlraum is part of the optical surface for directing light during a fusion experiment. Light is bounced off the interior of the hohlraum cylinder onto the capsule [7]. Any holes on the reflective area in the interior of the hohlraum cylinder are places where laser light energy is lost and not directed to the capsule. To minimize the loss of energy while maximizing the information for characterizing the ice layer the shapes of the hohlraum side windows are necessarily complex. These windows maximize the surface area used to reflect energy onto the capsule during a shot while providing sufficient information to assess the quality of the ice-layer and provide enough information to align the x-ray source, hohlraum windows and x-ray cameras (Fig. 8). When the matching front and back hohlraum windows are aligned, two half circles provide a view of the capsule ice-layer during an x-ray image.

To create x-ray images of the capsule, three orthogonal views of the capsule are made with three separate x-ray point sources and x-ray camera pairs. The hohlraum design includes four windows on the sides of the hohlraum cylinder. There is also an un-obstructed view of the capsule from the top and bottom of the hohlraum cylinder. For the hohlraum side images, the window closest to the x-ray point source is smaller than the window closest to the x-ray camera. This window scale change corresponds to the expansion of the x-ray image as it propagates away from the point x-ray source.

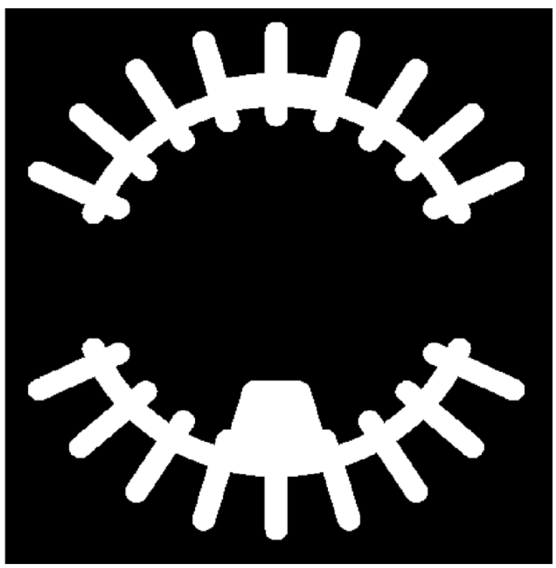

Figure 8: X-ray image of the capsule from the hohlraum side when the x-ray source, x-ray cameras and hohlraum windows are aligned.

To align an x-ray source to the x-ray camera, individual images are processed to determine corrections to the position and angle of each camera and x-ray source pair. This is analogous to the pointing and center done for most deployed automatic alignment loops, but with a few additional complexities. First, when the front and back windows are missaligned, the front and back hohlraum windows block overlapping parts (Fig. 9). Since there is no reliable way to determine which parts of the x-ray source are blocked from front or back hohlraum window, it is difficult to determine reliably the direction of movement to correct alignment errors. To handle this complexity, a new control loop type was needed.

Figure 9: X-ray image of the capsule from the hohlraum side when the x-ray source, x-ray cameras and hohlraum windows are not aligned.

The control loop to align the x-ray imager to the hohlraum involves two main tasks. The first task is image processing. The image processing estimates the magnitude of the adjustment needed to maximize the exposed area through both hohlraum windows [9]. The horizontal and vertical error magnitudes are calculated separately.

The second task is to use the horizontal and vertical error magnitude to make four separate tests. The loop performs four test moves of all four combinations of positive and negative moves of the x-ray source and camera. For each of the four test moves, the resultant remaining error magnitude is measured. The test move with the smallest remaining error magnitude is determined to be the best move and becomes the starting point for the next iteration. If the remaining error magnitude is within tolerance, the control loop is defined as aligned. If not, another set of four test moves is performed and tested.

Using emulated image generation, this new control loop was tested for over 200,000 hohlraum alignment initial conditions. For all 200,000 initial conditions define by the mechanical constraints, the new control loop converges within twenty adjustments. The average alignments take five adjustments.

3. SUMMARY

The number of control loops needed for NIF alignment continues to increase due to refinement of alignment tasks and the addition of new hardware. As the NIF facility is used more for experiments, the monitoring of system performance through logged performance metrics will be imperative. There will continue to be refinement of the automatic alignment system to improve accuracy, speed and robustness based on system performance metrics. There will also be new hardware added. The automatic alignment system will continue to be upgraded as long as required to meet NIF and resource allocation.

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